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FLIGHT SERVICE ENVIRONMENTAL EFFECTS ON COMPOSITE MATERIALS AND STRUCTURES

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SUMMARY

NASA Langley and the U.S. Army have jointly sponsored programs to assess the effects of realistic flight environments and ground-based exposure on advanced composite materials and structures. Composite secondary structural components were initially installed on commercial transport aircraft in 1973; secondary and primary structural components were installed on commercial helicopters in 1979; and primary structural components were installed on commercial aircraft in the mid-to-late 1980's. Over 5.3 million total component flight hours have been accumulated on 350 composite components since 1973. Service performance, maintenance characteristics, and residual strength of numerous composite components are reported. In addition to data on flight components; 10-year ground-based exposure test results on material coupons are reported. Comparisons between flight and ground-based environmental effects for several composite material systems are also presented. Test results indicate excellent in-service performance with the composite components during the 15 year evaluation period. Good correlation between ground-based material performance and operational structural performance has been achieved.

INTRODUCTION

The influence of operational and ground-based environments on the long-term durability of advanced composite materials and aircraft components fabricated from them is an ongoing concern of aircraft manufacturers and airline operators. Some of the uncertainties include the effects of moisture absorption, temperature cycling, ultraviolet radiation, lightning strikes, and long-term sustained stress. As a result of these concerns, NASA Langley and the U.S. Army initiated flight and ground-based environmental effects programs to assess the performance of composite materials and structures when subjected to normal operational environments. Secondary and primary structural composite components have been in service on transport aircraft and helicopters since the early 1970's. Service performance has been documented and residual strength tests were performed to assess the effects of flight environments on structural performance. Since most aircraft spend a considerable portion of their service life on the ground, a series of coupon tests were performed to assess the effects of ground-based environments on several composite material systems. Residual strength, stiffness, and moisture absorption as a function of exposure time were determined and the results are compared with tests on composite structural components removed from service. The purpose of this paper is to summarize the results of 10 years of environmental exposure of composite materials and to discuss results for 15 years of flight service of composite components on transport aircraft and helicopters.

FLIGHT SERVICE EVALUATION OF COMPOSITE COMPONENTS

In 1973 the NASA Langley Research Center initiated a series of programs to evaluate the effects of realistic flight environments on composite components. The objective was to establish confidence in the long-term durability of advanced composites through flight service of numerous composite components on transport aircraft. Emphasis was on commercial aircraft because of their high utilization rates, exposure to worldwide environmental conditions, and systematic maintenance. The experimental composite components allowed the airlines to develop inspection and repair procedures prior to making production commitments. In 1979 NASA Langley and the U.S. Army initiated joint programs to evaluate composite components on commercial and military helicopters. Although helicopters accumulate fewer flight hours than transport aircraft, in many instances the environments and fatigue loading are more severe for the helicopter components. Primary emphasis for the helicopter components is to establish the effects of realistic operating service environments on the strength of primary and secondary composite components. These environmental factors can then be applied with more confidence and less conservatism in the future design of composite components.

Component Description

The transport aircraft that are flying composite components in the NASA Langley service evaluation program are shown in figure 1. Eighteen Kevlar-49/epoxy fairings have been in service on Lockheed L-1011 aircraft since 1973. In 1982, eight graphite/epoxy ailerons were installed on four L-1011 aircraft for service evaluation. One hundred and eight B737 graphite/epoxy spoilers have been in service on seven different commercial airlines in worldwide service since 1973. Ten B737 graphite/epoxy horizontal stabilizers have been installed on five aircraft for commercial service. Fifteen graphite/epoxy DC-10 upper aft rudders have been in service on twelve commercial airlines and three boron/aluminum aft pylon skin panels were installed on DC-10 aircraft in 1975. One graphite/epoxy vertical stabilizer was installed on a DC-10 aircraft in 1987. Ten graphite/epoxy elevators have been in service on B727 aircraft since 1980. In addition to the commercial aircraft components indicated in figure 1, two boron/epoxy reinforced aluminum center-wing boxes have been in service on U.S. Air Force C-130 transport aircraft since 1974. Details of the structural design concept and manufacturing procedures used for each component can be found in reference 1. The transport airlines/operators participating in the NASA Langley flight service program are listed in figure 2. The airlines were selected to represent diverse climatic conditions and route structures.

The helicopters that are flying composite components in the NASA Langley/U.S. Army service evaluation program are shown in figure 3. Forty shipsets of Kevlar-49/epoxy doors and fairings and graphite/epoxy vertical fins have been installed on Bell 206L commercial helicopters for 10 years of service evaluation. The helicopters are operating in diverse environments in Alaska, Canada, U.S. Gulf Coast, Northeast U.S., and Southwest U.S. Selected components are periodically removed from service for residual strength testing. Details on the design, fabrication, and test of the Bell 206L composite components can be found in reference 2.

Ten graphite/epoxy tail rotors and four hybrid Kevlar-49-graphite/epoxy horizontal stabilizers were removed periodically from Sikorsky S-76 production helicopters to determine the effects of realistic operational service environments. Static and fatigue tests were conducted on the components removed from service, and the results were compared with baseline certification test results. Details on the design, fabrication, and test of the S-76 composite components are reported in reference 3.

A Kevlar-49/epoxy cargo ramp skin is installed on a U.S. Marine Corps CH-53D helicopter for service evaluation. Details of the design, fabrication, and installation of the cargo ramp skin are reported in reference 4. The helicopter airlines/operators participating in the NASA Langley/U.S. Army flight service program are listed in figure 4.

As indicated in figure 5, the NASA Langley flight service program that was initiated in 1973 included a total of 350 composite components. As of June 1991, 139 components were still in service; more than 5.3 million component flight hours had been accumulated, with the high-time aircraft having more than 58,000 flight hours. Some components were removed from service for residual-strength testing, and others were retired due to damage or other service-related problems that are discussed herein.

MAINTENANCE, REPAIR, AND STRUCTURAL PERFORMANCE

Transport Components

For the first several years of the flight service evaluation program, the composite components were tracked and inspected by aircraft manufacturer engineering personnel. Later in the program, maintenance and repair data were obtained from the airline maintenance personnel. Overall, the composite components have performed better than conventional metallic structures because of reduced corrosion and fatigue problems. However, some operational maintenance concerns surfaced with the composite components during the 15 year service evaluation. Some of the concerns were considered to be minor, whereas some of the components may require design changes before the aircraft manufacturers are ready to commit to production of composite components. One area that needs more attention in future designs is improved lightning protection schemes.

L-1011 Kevlar-49/Epoxy Fairings

The photographs shown in figure 6 indicate various types of damage incurred by the L-1011 Kevlar-49/epoxy fairings in service. Minor impact damage from equipment and foreign objects has been noted on several fairings, primarily the honeycomb sandwich wing-to-body fairings. Surface cracks and indentations have been repaired with filler epoxy and, in general, the cracks have not propagated with continued service. Paint adherence has been a minor problem, particularly for parts that have been in contact with hydraulic fluid. Frayed fastener holes have been noted in several fairings, primarily due to nonoptimum drilling procedures and improper fit. Elongated holes have been noted, primarily due to improper fit and nonuniform fastener load distribution. There have been no moisture intrusion problems with the Kevlar-49/epoxy fairings, and they have performed similar to production fiberglass/epoxy fairings. The fairings are still in service, and the three participating airlines are monitoring their performance during normal maintenance inspections. Additional details on the design, fabrication, and service evaluation of the Kevlar-49/epoxy fairings are presented in references 5 and 6.

B737 Graphite/Epoxy Spoilers

The B737 spoiler skins were fabricated with three different graphite/epoxy systems: T300/5209, T300/2544, and AS/3501. Aluminum honeycomb substructure and aluminum fittings were similar to those used in production aluminum spoilers. During the 15 year service evaluation period, several types of in-service damage were encountered. Over 75 percent of the damage incidents were related to design details. The most prevalent damage was caused by actuator rod interference with the graphite/epoxy skin. This problem was resolved by redesigning the actuator rod ends. The second most frequent damage was caused by moisture intrusion and corrosion at the splice between the center hinge fitting and spar. This damage could be prevented by redesigning the splice to prevent disbonds between the skin and spar cap. Miscellaneous cuts and dents related to airline usage were also encountered. Damage due to hailstone, bird strike, and ground handling equipment was noted on several spoilers. Minor repairs were performed by the airlines after proper instruction by Boeing repair personnel. Because of the expense involved, spoilers with major damage were removed from service.

A typical corrosion damage scenario for a splice between the center hinge fitting and spar is shown in figure 7. The corrosion damage can be characterized by three phases of development. Phase 1 involves corrosion initiation at an aluminum fitting or at the aluminum spar splice. The corrosion initiates due to moisture intrusion through cracked paint and sealant material. If the corrosion products are not removed and new sealant applied, the damage progresses to phase 2 where moisture penetrates under the graphite/epoxy skin along the aluminum C-channel front spar. Normal service loads combined with moisture contribute to crack growth and subsequent corrosion. If the phase 2 corrosion is not repaired, the damage progresses to phase 3 where extensive skin-to-spar separation takes place. Phase 3 corrosion can result in significant strength and stiffness loss. It takes about 2 years for the corrosion to progress from phase 1 to phase 3. Design changes and improved sealing methods could prevent corrosion damage in composite-metal interfaces.

Residual strength tests were conducted on 37 graphite/epoxy spoilers to establish the effects of service environments. The spoilers were tested with compression load pads on the upper surface to simulate airloads. Trailing edge tip deflection was measured as a function of applied load for each spoiler tested. The test results are compared with the strength of 16 new spoilers in figure 8. The strength for each spoiler through 6 years of service generally falls within the strength scatter band for the baseline spoilers. However, spoilers with significant corrosion damage which were tested after 7 and 8 years of service, respectively, indicated a 35 percent strength reduction. An additional T300/2544 spoiler with no corrosion damage was tested after 7-1/2 years of service, which verified that the 7 year strength reduction was related to corrosion damage. Three spoilers tested after 9 years of service with little or no corrosion damage exhibited strengths equal to the strength of the baseline spoilers. An AS/3501 spoiler with 10 years of service and known corrosion damage failed at 78 percent of the average strength of the baseline spoilers. Two other spoilers with 10 years of service with no corrosion damage failed within the baseline strength scatter band. Spoilers tested after 12 years of service failed at or above the average strength of the baseline spoilers. One spoiler that had known corrosion damage after 15 years of service failed at about 75 percent of the strength of baseline spoilers.

Load-deflection response of spoilers with 10 years and 15 years of service time are compared with the response of baseline spoilers in figure 9. The 10 year spoiler with known corrosion damage failed at about 78 percent of the baseline strength. However, the 15 year spoiler with almost 38,000 flight hours failed at about 8 percent above the baseline strength. Additional details of service experience with the spoilers can be found in reference 7.

DC-10 Boron/Aluminum Aft Pylon Skins

One of the three boron/aluminum skin panels on the DC-10 aircraft was removed from service after 7 years because of corrosion damage. The photograph shown in figure 10 indicates that the outer layer of boron filaments on the inside of the panel was almost completely exposed. The panel contained a light residue of ester oil similar to engine oil; however the specific corrodent was not identified. A second panel also had some corrosion damage and a small crack, but the panel is still in service and is being monitored closely to check for crack growth and further corrosion damage. The crack in the panel was probably caused by exterior mechanical damage during removal and reinstallation of the panel during inspection. It has been concluded that the method of corrosion protection used was inadequate. In general, the boron/aluminum panels have not performed as well as similar production titanium panels. Additional details on the DC-10 boron/aluminum skin panels are presented in reference 8.

DC-10 Graphite/Epoxy Rudders

There have been several incidents which required rudder repairs. The damage sustained by the rudders included minor disbonds, rib damage due to ground handling, and skin damage due to lightning strike. Figure 11 shows minor in-service lightning strike damage to the trailing edge of a rudder and rib damage that occurred while a rudder was off the aircraft for other maintenance. The lightning strike damage was limited to the outer four layers of graphite/epoxy and a room temperature repair was performed in accordance with procedures established at the time the rudders were certified by the FAA. The rib damage was more extensive and a portion of a rib was removed and rebuilt. A detailed discussion of the repair procedure is given in reference 9.

More extensive lightning damage was sustained on another graphite/epoxy rudder as shown in figure 12. Upon inspection of the rudder, it was discovered that the lightning protection strap was inadvertently left off after the previous maintenance check. The skin in the damaged area is eight plies thick over an 8-ply spar cap. Fiber damage and resin vaporization extended through the skin forward of the spar, and the skin and spar cap aft of the rear spar were completely destroyed. Details of the repair procedures are given in reference 10.

A graphite/epoxy rudder was removed from service for residual strength testing after 5.7 years and 22,265 flight hours on Air New Zealand. The load-deflection response shown in figure 13 indicates that the 5.7-year rudder had an initial stiffness higher than the baseline rudder, but the overall response is similar for the two rudders. The baseline and the 5.7-year tests were stopped at approximately 400 percent limit load because of an instability of the loading apparatus. Although the rudders are designed by stiffness considerations and only one residual strength test has been conducted, the overall response of the rudder indicates that no degradation has occurred as a result of over 22,000 flight hours.

B727 Graphite/Epoxy Elevators

Since initiation of flight service of 10 elevators in 1980, there have been four B727 graphite/epoxy elevators damaged by minor lightning strikes and two elevators damaged during ground handling. Damage from lightning strikes ranged in severity from scorched paint to skin delamination. Figure 14 shows typical lightning damage to the trailing edge of an elevator and trailing edge fracture of another elevator caused by impact from a deicing apparatus. The most severe damage to an elevator occurred when the static discharge probe of one B727 penetrated the elevator of another B727 during ground handling. Skin panels were punctured, four holes in the lower surface and one hole in the upper surface, and the lower horizontal flange at the front spar was cut inboard of the outboard hinge. All the elevator repairs were performed by airline maintenance personnel.

The lightning damage was repaired with epoxy filler and milled glass fibers. The skin punctures were repaired with T300/5208 prepreg fabric and Nomex honeycomb core plugs. The front spar was repaired with a machined titanium doubler, which was mechanically fastened to the lower skin flange of the spar chord. The repaired graphite/epoxy elevators are in storage and can be reinstalled for continued service. Details of the design and fabrication of the graphite/epoxy elevators are given in reference 11.

L-1011 Graphite/Epoxy Ailerons

During the 9 year service evaluation period there have been no damage incidents or major maintenance actions required. Minor paint touch-up has been performed periodically and loose fibers around one fastener hole on the Lockheed company aircraft were rebonded with epoxy. Details of the flight service evaluation program are reported in reference 12.

B737 Graphite/Epoxy Horizontal Stabilizers

There have been three reported damage incidents on the B737 horizontal stabilizers. De-icer impact damage was induced on the upper surface panel of both stabilizers on one aircraft. These impacts were minor and damage was limited to the skin, not affecting the stiffener elements. The third stabilizer was damaged when a broken fan blade penetrated the lower surface of the stabilizer. The penetration missed the stiffener elements and damage was limited to a small area of the skin panel. All three of the stabilizers were repaired on the aircraft using wet lay-up cure techniques per specifications developed by Boeing. Figure 15 shows details of the in-service repair process.

One of the B737 aircraft with composite stabilizers crashed in Alaska in June 1990. The graphite/epoxy stabilizers were returned to Boeing for inspection, teardown, and testing. Figure 16 shows a photograph of one of the stabilizers. No "non-crash" induced delaminations were found and there was no corrosion of metal-composite interfaces. These results indicate the effectiveness of the fiberglass isolation system that was used to prevent galvanic corrosion between graphite and metal parts. Boeing plans to conduct residual strength tests on material coupons machined from skin panels and compare results with baseline tests. Details on the development of the graphite/epoxy horizontal stabilizers are reported in reference 13.

DC-10 Graphite/Epoxy Vertical Stabilizer

One graphite/epoxy vertical stabilizer has been in service on a DC-10 aircraft since January 1987. Three inspections have been performed by Douglas engineering personnel and no defects have been found. The graphite/epoxy Nomex honeycomb skin panels have been x-rayed and no moisture has been found in the core. Ultrasonic inspections of solid laminates have been conducted annually and no disbonds or other defects have been indicated.

C-130 Boron/Epoxy Reinforced Wing Box

Two boron/epoxy reinforced wing boxes have been in service on U.S. Air Force C-130 aircraft since 1974. The wing boxes have been inspected regularly by U.S. Air Force personnel and no damage or defects have been found. These wing boxes provide significant improvement in fatigue life compared to conventional aluminum boxes.

Helicopter Components

The helicopter components involved in the NASA/U.S. Army flight service evaluation program have been installed on Sikorsky S-76 and Bell 206L commercial helicopters. The S-76 graphite/epoxy tail rotor spars and the hybrid graphite-Kevlar/epoxy horizontal stabilizers are production parts. These parts are subjected to normal maintenance inspection for damage every 100 flight hours and an inspection for structural damage annually or after 1000 flight hours. The Bell 206L Kevlar/epoxy fairings and doors and the graphite/epoxy vertical fins are inspected annually or after 1200 hours of service for evidence of damage, repair, excessive wear, or weathering. Except for Kevlar/epoxy baggage doors on the 206L, the composite components have demonstrated good service performance. Because of poor bonding between facesheets and honeycomb core, the 206L baggage doors were removed from the service evaluation program.

Sikorsky S-76 Composite Components

Four horizontal stabilizers and 11 tail rotor spars have been removed from aircraft and tested over a 9 year evaluation period. The components were inspected prior to residual strength testing and no significant service-induced defects or damage were found. Figure 17 shows predicted and measured moisture absorption data and strength retention of AS1/6350 tail rotor spars. All the spars were removed from helicopters operating in the Louisiana Gulf Coast region. Weather data from Lake Charles, LA were used in predicting the moisture absorption profile. Measured moisture absorption values shown in figure 17 are below the prediction by 0.05 to 0.15 percent for service times up to 40 months and are above the predicted values by 0.1 to 0.30 percent for service times beyond 70 months. During the development of design allowables and FAA certification testing, Sikorsky conducted accelerated conditioning at 87 percent relative humidity and 88°C on material coupons. The predicted moisture saturation level for AS1/6350 graphite/epoxy was 1.1 percent. After 9 years of service, the moisture level in the AS1/6350 tail rotor spars was slightly below 1.0 percent. Cyclic shear stress as a function of cycles to failure for the flight service tail rotor spars is shown in figure 17, along with data for baseline dry spars tested at room temperature for FAA certification. The shape of the curves was based on interlaminar shear fatigue tests. The results in figure 17 indicate a 95 percent strength retention for the service exposed spars compared to the baseline strength data used for certification.

Structural response of the S-76 composite horizontal stabilizers is shown in figure 18. Proof load deflection data for the four stabilizers returned from service indicate deflections below the maximum allowable deflection of 0.41 cm, indicating no significant stiffness loss. The maxi. um moisture content for the stabilizers, 0.49 percent, occurred after 91 months of service and 5846 flight hours. Full moisture saturation has not yet been reached. Vibratory roll moment as a function of cycles to failure is plotted in figure 18. The three stabilizers with 56, 66, and 91 months of service were fatigue tested at applied loads exceeding loads used for FAA certification. The average vibratory roll moment at failure for the service exposed stabilizers was approximately 2 percent higher than the corresponding roll moment for the baseline stabilizers used for certification. The shape of the curves was established by evaluating graphite/epoxy and Kevlar/epoxy coupons in the laboratory. The same shape was assumed to apply to full scale components. Additional details on the S-76 flight service program can be found in reference 14.

Bell 206L Composite Components

A total of 78 composite components have been removed from service for structural testing. The exposure times range from 12 to 84 months and flight times range from 386 to 6750 hours. Moisture absorption and strength retention data for T300/E-788 vertical fins are shown in figure 19. The moisture content was determined by drying plugs removed from the fins. The plugs included painted graphite/epoxy skins, adhesive, and honeycomb core material. The average moisture content measured for the fins is approximatley 1.1 percent by weight. The fins operating in the humid Gulf of Mexico had moisture contents slightly higher than those for fins operating in other exposure locations. The residual strengths for 15 fins removed from service exceeded the design ultimate strength requirement. Failure loads for 12 of the fins fall within the baseline scatter band for five fins selected at random. One of the fins operating in the northeast USA and Canada was struck by lightning. This fin was damaged at the top but no apparent damage was inflicted on the structural box. This damaged fin failed below the baseline scatter band, but well above the design ultimate requirement.

Moisture absorption and strength retention data for Kevlar-49/F-185 litter doors are shown in figure 20. Average moisture content for the litter doors is approximately 2.0 percent. This high moisture content was expected since laboratory tests and other outdoor exposure tests indicated that Kevlar/epoxy composites absorb about twice the moisture of graphite/epoxy composites. There is considerable scatter in the strength data for the 15 litter doors that were removed from service and tested. All the litter doors exceeded the design ultimate strength requirement. Seven litter doors failed above the baseline scatter band and five litter doors failed below the baseline scatter band. The large scatter is expected since some of the failures were a result of metal hinge failures and latch pins slipping from the test fixture.

Since the baggage doors had manufacturing defects and were removed from service, test results are not discussed herein. The forward fairings were designed by stiffness requirements and are considered to be secondary load-carrying components. All the fairings failed at loads at least a factor of nine above the design ultimate strength requirement. Additional details on the Bell 206L flight service evaluation program can be found in reference 15.

CH-53D Kevlar/Epoxy Cargo Ramp Skin

A Kevlar/epoxy composite skin was installed on the aft end of a CH-53D Cargo ramp for U.S. Marine Corps service evaluation in 1981. The panel has been inspected annually since installation and no damage or service related problems have been reported by the U.S. Marine Corps.

FLIGHT AND GROUND-BASED ENVIRONMENTAL EXPOSURE EFFECTS ON COMPOSITE COUPONS

In conjunction with the flight service evaluation program, NASA Langley and the U.S. Army initiated four flight and ground-based environmental exposure programs. The objectives of these programs were to supplement component data with less expensive coupon data, correlate ground exposure data with flight exposure data, and to assess the requirement for future flight service programs. The four programs are outlined in Figure 21. The first program, 10 year worldwide ground exposure, was structured to supplement flight data obtained through service evaluation of B737 spoilers, DC-10 rudders and L-1011 fairings. Since the largest number of components were installed on B737 aircraft, ground-based exposure locations were selected where B-737 aircraft with graphite/epoxy spoilers would be operating. The following exposure locations were selected: Hampton, VA; San Diego, CA; Honolulu, HI; Frankfurt, F.R.G.; Wellington, New Zealand; and São Paulo, Brazil. The materials selected for exposure were the B737 spoiler materials: T300/5209, T300/2544, AS/3501; the DC-10 rudder material: T300/5208; and the L-1011 fairing materials: Kevlar-49/F155 and Kevlar-49/F161. Compression and short beam shear test coupons were selected to represent matrix dominant failure modes; whereas flexure coupons were selected to represent a fiber dominant failure mode.

The second program, 10 year ground and flight exposure, was structured to compare ground and flight exposure data, compare the effects of solar versus nonsolar (partially shielded) exposure, compare the effects of aircraft interior and exterior exposure, and to assess the effects of long-term sustained stress. The exposure sites chosen were: Edwards AFB, CA; Dallas, TX; Honolulu, HI; and Wellington, New Zealand. These sites offered diverse climates with significant variations in temperature and humidity conditions. In addition to ground exposure, composite coupons were installed on top and bottom surfaces of B737 flap-track fairing tail cones and in the nonpressurized interior of the aircraft behind the aft pressure bulkhead. The objectives of these exposure locations were to compare the effects of direct solar and nonsolar exposure and to compare the effects of interior and exterior aircraft exposure. One additional material, T300/934, and an additional matrix dominate test $(+45/-45)_{2s}$ tension coupon were added to the list of materials and test coupons discussed previously.

The third program, 10 year Bell 206L ground exposure, was structured to support the Bell 206L helicopter flight service program. The composite materials used to fabricate the flight service components were used in the ground exposure program and are listed in figure 21. The ground exposure coupons were installed on racks in Hampton, VA; Cameron, LA, on a U.S. Gulf oil platform; Toronto, Canada; and Fort Greely, AK. The test coupons were configured for compression, short beam shear, and tension testing.

The fourth program, 9 year Sikorsky S-76 ground exposure, was structured to compare ground and flight data for two composite materials that were in production on S-76 commercial helicopters. The exposure locations selected were Stratford, CT and West Palm Beach, FL. The two exposure materials discussed previously for the flight components included AS1/6350 and Kevlar/5143. Compression, short beam shear, flexure, and tension coupons were exposed for moisture absorption determination and residual strength.

Geographic location of all the ground-based exposure racks is shown in figure 22. Coupons were removed from exposure racks at specified intervals ranging from 1-10 years of exposure. Selected coupons were dried and weighed to determine moisture content and the remainder of the coupons were subjected to residual strength testing. Most coupons were tested at room temperature, however some tests were conducted at 82°C.

10 Year Worldwide Ground Exposure

Triplicate unpainted coupons were mounted in exposure racks and placed on rooftops to receive maximum exposure to the environment. The average residual properties (moisture content, strength, and modulus of elasticity) were compared to average baseline properties. Test coupons were removed from the racks for evaluation after 1, 3, 5, 7, and 10 years of exposure. The objectives of the test in this exposure program were to establish the effects of various realtime outdoor environments on the moisture absorption and strength of composite materials and to compare the results with results obtained from flight service components.

The amount of moisture that composite materials absorb is a function of matrix and fiber type, temperature, relative humidity, and exposure conditions. Average moisture absorption (as a fraction of composite coupon weight) is plotted as a function of exposure time in figure 23 for the following exposure locations: Hampton, VA; San Diego, CA; Honolulu, HI; Frankfurt, F.R.G.; Wellington, New Zealand; and São Paulo, Brazil. The T300/5208 and T300/5209 graphite epoxy materials absorbed the least amount of moisture after the 10 year exposure period, about 0.7 percent. The AS/3501 graphite/epoxy absorbed slightly over 1.0 percent moisture during the 10 year exposure period. The T300/2544 graphite/epoxy suffered significant surface degradation due to ultraviolet radiation and absorbed about 2.0 percent moisture during the 10 years of exposure. The two Kevlar-49/epoxy materials absorbed approximately 2.5 percent moisture during the 10 year exposure period. These results are expected since the Kevlar fibers also absorb moisture. The Brazil and New Zealand exposures resulted in the highest moisture absorption for all the materials. These results are expected since the average annual humidity in São Paulo, Brazil and Wellington, New Zealand is about 75 to 80 percent. Specific moisture data for each exposure site can be found in reference 1.

Moisture absorption for material coupons is compared with moisture absorption data for plugs removed from B737 graphite/epoxy spoilers in figure 24. The coupon data are for three unpainted graphite/epoxy materials exposed at San Diego, CA and São Paulo, Brazil for 10 years. The spoiler data are for painted honeycomb sandwich plugs removed from spoilers that had flown for 10 years on Frontier and VASP airlines. The results indicate that the unpainted ground exposed coupons absorbed significantly more moisture than the painted flight spoilers. Although the spoilers spend a significant portion of time on the ground, it is expected that the flight profile would tend to dry out the outer surface of the material.

The average room temperature residual strengths (flexure, short beam shear, and compression) of six composite materials for 10 years of outdoor exposure at the six exposure sites discussed previously are plotted in figure 25. The graphite/epoxy coupons were fabricated with 0-degree tape and the Kevlar/epoxy coupons were fabricated with (0/90) fabric. Three-point flexure tests were conducted to assess the effects of outdoor environments on surface fiber strength. The coupons were tested with the exposed surface in compression; in general, however, failure occurred in tension at mid-span of the coupons. After 10 years of exposure, the Kevlar-49/F155 material indicated the largest flexural strength loss, about 20 percent. The T300/2544 material, which had significant surface degradation in the resin, failed at about 13 percent below the average baseline strength. The matrix dominant compression coupons indicated a similar strength loss, 15 to 20 percent, during the 10 year exposure.

The maximum strength loss for the matrix dominant short beam shear coupons was about 23 percent. Strengths of the Kevlar-49/F155 and T300/2544 materials were consistently below the baseline scatter band between 3 and 10 years of exposure. The two Kevlar/epoxy materials also indicated a loss in modulus ranging from 20 to 28 percent during the 10 year exposure. These results, along with detailed data plots for each exposure site, are reported in reference 1.

Ten year compression strength data for material coupons are compared with B737 graphite/epoxy spoiler strength data in figure 26. The strength data are for coupons and spoilers with the same exposure conditions that were discussed for the moisture comparison of figure 24. Except for one spoiler with known corrosion damage, the spoilers exhibited residual strengths that were slightly higher than the coupon residual strengths. As discussed previously, the spoiler corrosion damage is a design related problem and could be prevented through design changes. These results indicate excellent strength correlation between ground exposed coupons and flight exposed spoilers.

10 Year Ground and Flight Exposure

Coupon exposure locations for the flight portion of this program are shown in figure 27. Short beam shear, flexure, and tension coupons were mounted on the upper (solar) and lower (nonsolar) surface of B737 flap-track fairing tailcones to represent exterior aircraft exposure. Short beam shear, flexure, compression, stressed tension, and unstressed tension coupons were mounted inside the unpressurized tailcone area of the aircraft. The sustained stress tension coupons were stressed at 20 percent of baseline failure loads with the aid of a calibrated torqued bolt/Bellville spring washer load system. The ground exposure coupons are shown in figure 28. One side of the

exposure rack has coupons mounted for direct solar radiation and one side is shielded to prevent direct solar radiation. A phenolic honeycomb core was mounted above the coupons to prevent direct ultraviolet radiation impingement, however, the core allowed adequate air circulation and allowed precipitation to drain down the individual cells and onto the coupons.

The effect of ground exposure on compression strength of T300/5208, T300/5209, and T300/934 graphite/epoxy materials is shown in figure 29. The results are for coupons exposed on the shielded nonsolar side of the exposure rack at Dallas, TX. Tests were conducted at room temperature and at 82°C. However results are shown for the room temperature tests only since extensive grip failures were evident at 82°C. Results indicate that most coupons failed at or above the baseline failure strengths. The maximum compression strength loss was about 15 percent for the T300/934 material after 10 years of exposure.

The effects of flight and ground exposure on short beam shear strength of three graphite/epoxy materials is shown in figure 30. The results are for coupons exposed on the upper (solar) surface of B737 flap-track fairing tailcones on Aloha Airlines and for solar exposed material coupons at Honolulu, HI. The coupons were tested at 82°C and are compared to baseline coupons that were also tested at 82°C. An unexplained trend is evident; a significant strength loss after 2 to 3 years of exposure with an increase in strength thereafter. A maximum short beam shear strength loss of 40 percent was evident for the T300/5209 material after 2 years of exposure on Aloha Airlines. However, after 10 years of exposure, strength losses of only 13 to 25 percent occurred. The T300/934 material cures at 177°C, compared to 121°C for the T300/5209 material, however the T300/934 material performed only slightly better in the 82°C test. The coupons exposed at Honolulu, HI performed the same or slightly better than the coupons exposed on the Aloha Airlines aircraft. The results of these tests indicate that the less expensive ground-based tests could be used to assess material performance for future evaluations.

A comparison between interior and exterior aircraft exposure effects on flexure strength of three graphite/epoxy materials is shown in figure 31. The results are for coupons exposed on the upper (solar) surface and lower (nonsolar) surface of B737 flap-track fairing tailcones and in the interior of Southwest Airlines aircraft. The coupons were tested at 82°C and compared to baseline coupons tested at 82°C. A maximum strength reduction of 20 percent occurred for the T300/5209 material exposed on the upper surface of the flap-track fairing tail cone. Considering test data scatter, there is no discernible difference between the effects of solar exterior, nonsolar exterior or aircraft interior exposure.

The effects of sustained stress on tensile strength of three graphite/epoxy materials exposed outdoors at the NASA Dryden Research Center in Edwards Air Force Base, CA, are shown in figure 32. The unstressed coupons are compared with coupons that were continuously stressed at 20 percent of the baseline failure stress. The tensile coupons were tested at 82°C. The test results indicate no discernible difference between the stressed and unstressed coupon data. Small variations above and below baseline values are indicated during the 10 year evaluation period. Additional details on the ground and flight exposure program are reported in reference 16.

10 Year Bell 206L Ground Exposure

Moisture absorption data for three Kevlar/epoxy fabrics and one graphite/epoxy tape material are shown in figure 33. The painted T300/E-788 graphite/epoxy material absorbed about 0.7 percent moisture, whereas the painted Kevlar/epoxy materials absorbed about 2.5 percent moisture, as expected. The average residual strengths for four Bell 206L composite materials after outdoor exposure at five exposure sites discussed previously are shown in figure 34. In the summer of 1985 the exposure racks located at Cameron, LA and on the off-shore oil platform were destroyed by hurricanes. Therefore, the data for 5, 7, and 10 years of exposure are from racks located in Hampton, VA, Toronto, Canada, and Fort Greely, AK. Six replicates for each exposure site were tested for each exposure period. The residual compression strength varies between 88 and 101 percent of the baseline strength. The short beam shear strength varies between 89 and 104 percent of the baseline strength. The Kevlar-49/LRF-277 material exhibited the largest compression and shear strength reductions and the T300/E-788 exhibited no strength reduction. The residual tension strengths for all four materials were within the baseline scatter band for all exposure periods up to 10 years.

Figure 35 compares strength retention and moisture absorption data for T300/E-788 composite coupons with corresponding data from Bell 206L vertical fins after 5 years of flight service. The vertical fins absorbed about 1.1 percent moisture, whereas the 5 year ground exposed coupons absorbed about 0.7 percent moisture. The fin moisture content includes moisture absorbed by paint, sealer, primer, graphite/epoxy skins, and honeycomb core. Strength retention for compression coupons and vertical fins was near 100 percent. These results indicate that ground-based coupon strength data are representative of strength retention results expected from flight service components. Additional details on the test program and test results are reported in reference 15.

Nine Year Sikorsky S-76 Ground Exposure

As discussed previously, Sikorsky conducted accelerated laboratory conditioning tests to develop environmental factors that account for anticipated strength reduction as a function of absorbed moisture. These tests were conducted at 87 percent relative humidity and 88°C. To establish a correlation between realtime outdoor exposure and accelerated laboratory exposure, composite panels were exposed for 9 years in outdoor racks located at Stratford, CT and West Palm Beach, FL. Results for 6-ply AS1/6350 short beam shear and flexure coupons machined from the panels are shown in figure 36. Residual strength is plotted as a function of absorbed moisture and the results indicate that the matrix dependent short beam shear strength is affected more than the fiber dependent flexure strength. The accelerated laboratory conditioning tests indicated moisture saturation for the 6-ply laminates at about 1.1 percent. The panels exposed at Stratford, CT absorbed a maximum of 1.13 percent moisture, however, the panels exposed at West Palm Beach, FL absorbed a maximum of 1.40 percent moisture. The results are inconsistent in that the 5 year panels absorbed the most moisture, whereas the 9 year panels absorbed the least amount of moisture. These results are probably affected by local weather conditions at the time of panel removal.

Strength retention trends parallel the accelerated laboratory test data. The residual flexure strengths for exposed laminates exceed 95 percent of the baseline room temperature dry strength and also meet or exceed the strength of the accelerated conditioned specimens. Residual short beam shear strengths for exposed laminates vary between 70 and 90 percent of the baseline strength and are within 1 percent of the strength of the accelerated conditioned specimens. Additional details of the ground exposure test program can be found in reference 14.

CONCLUDING REMARKS

The influence of ground-based and aircraft operational environments on the long-term durability of several advanced composite materials and structural components has been studied. Results of 10 years of outdoor exposure indicate that Kevlar/epoxy material systems were more affected by the various environments than were graphite/epoxy material systems. Residual strength tests were conducted to establish the effects of various environments on composite materials. Differences

in the effects of solar versus nonsolar exposure, aircraft interior exposure versus aircraft exterior exposure, and sustained stress versus unstressed exposure were not discernible. Some of the differences that might be expected were masked by data scatter.

Numerous aircraft and helicopter composite components have been in service for more than 15 years and excellent operational performance has been achieved. Normal maintenance and in-service related damage such as ground handling damage, foreign object damage, and lightning strikes have occurred. Design related corrosion damage was experienced on aluminum fittings and splices on some graphite/epoxy reinforced spoilers. Excellent service and residual strengths have been achieved with composite horizontal and vertical stabilizers and tail rotor spars during 9 years of helicopter service.

Good performance correlations between ground exposed material coupons and flight service components indicate that ground-based exposure data should be sufficient to predict long-term behavior of composite aircraft structures. It is important to note that at the coupon level, nothing was learned from exposing materials on the aircraft that could not be learned from ground-based exposure. A significant cost saving during aircraft design development would be a major benefit.

Lessons learned in the NASA Langley/U.S. Army program indicate that additional research is needed to select better material test methods that result in less data scatter. The environmental exposure programs described in this report would have benefited if more baseline and post exposure replicates had been planned. Future exposure programs should consider exposing larger panels that are more representative of aircraft structure. The logistics of tracking materials would be lessened and more flexibility in selecting test coupons would be available.

The results of this program indicate that composite materials can be applied to the next generation of aircraft with a high degree of confidence. With proper design on the part of the aircraft manufacturer, the airlines and operators of future aircraft should expect reduced corrosion and fatigue concerns compared to conventional metallic structures.

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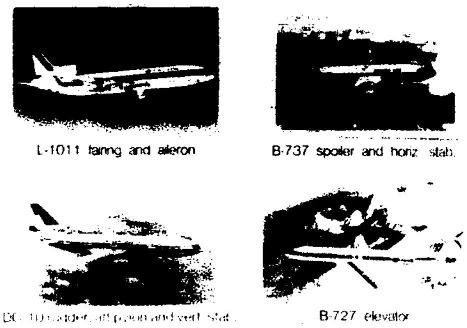

Figure 1. Flight service composite components on transport aircraft.

L-1011 K/E Fairings

- Eastern
- Air Canada
- TWA

C-130 B/E Reinforced Wing Boxes

- U.S. Air Force

DC-10 B/Al Aft Pylon Skins

- United

DC-10 G/E Rudders

- Korean
- Swiss Air
- Federal Express
- Mozambique
- Western
- Lan Chile
- Air Siam
- Continental
- Trans-International
- Finn Air
- Air New Zealand
- Trans-America

B-727 G/E Elevators

- United

B-737 G/E Spoilers

- Air New Zealand
- Lufthansa
- Piedmont
- Frontier
- VASP
- PSA
- Aloha

L-1011 G/E Ailerons

- Delta
- TWA

B-737 G/E Horizontal Stabilizer

- Delta
- Mark Air

DC-10 G/E Veritical Stabilizer

- Finn Air

Figure 2. Airlines and operators participating in composite flight service program for transport aircraft.

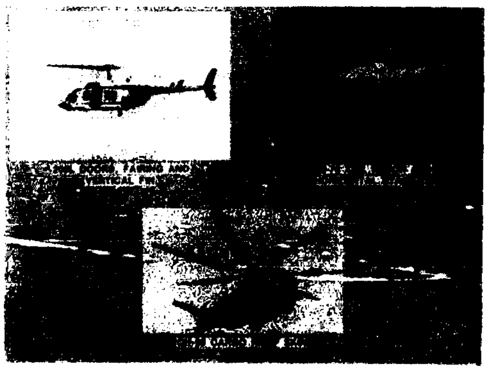

Figure 3. Flight service composite components on helicopters.

Bell 206L Composite Components

- Island Helicopter
- ERA Helicopters
- Trans Quebec Helicopters
- Royal Canadian Mounted Police
- Heli-Voyageur
- Commercial Helicopters
- Pumpkin Air
- Air Logistics
- Petroleum Helicopters, Inc.
- Houston Helicopters
- Clearwater Foods
- Air Services International
- Viking Helicopters
- Canadian Dept. of Transportation

Sikorsky S-76 Composite Components

- Air Logistics

CH-53 K/E Cargo Ramp Skin

- U. S. Marine Corps

Figure 4. Airlines and operators participating in composites flight service program for helicopters.

Aircraft Component	Total Components		Start of Flight Service	Cumulative Flight Hours High Time Aircraft	Cumulative Flight Hours Total Component
L-1011 Fairing panels	18	(15)	January 1973	52,610	742,630
737 Spoiler	108	(33)	July 1973	45,260	2,747,760
C-130 Center wing box	2	(2)	October 1974	10,920	21,520
DC-10 Aft pylon skin	3	(2)	August 1975	45,640	107,840
DC-10 Upper aft rudder	15	(10)	April 1976	58,340	519,430
727 Elevator	10	(8)	March 1980	40,930	336,610
L-1011 Aileron	8	(8)	March 1982	31,720	249,480
737 Horizontal stabilizer	10	(8)	March 1984	19,620	189,800
DC-10 Vertical stabilizer	1	(1)	January 1987	17,580	17,580
S-76 Tail rotors and horizontal stabilizer	14	(0)	February 1979	5,860	53,150
206L Fairing, doors, and vertical fin	160	(51)	March 1981	11,325	440,000
CH-53 Cargo ramp skin	1	(1)	May 1981	5,000	5,000
Grand total	350	(139)			5,377,650

( ) Still in service June 1991

Figure 5. NASA composite structures flight service summary.

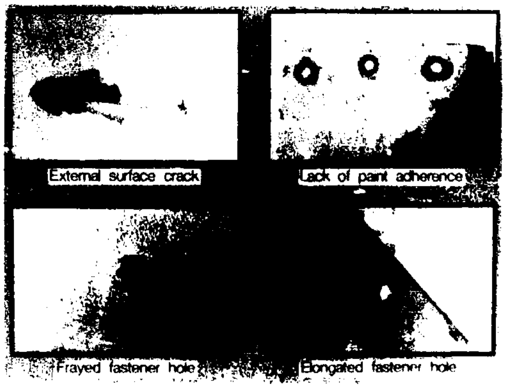

Figure 6. Typical in-service conditions of L-1011 Kevlar/epoxy fairings.

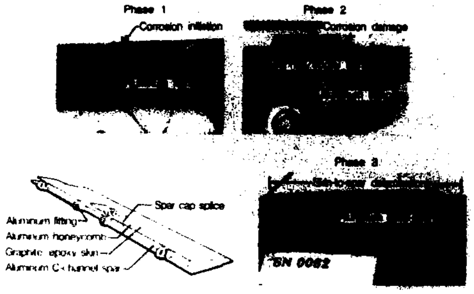

Figure 7. Corrosion of B737 graphite/epoxy spoilers.

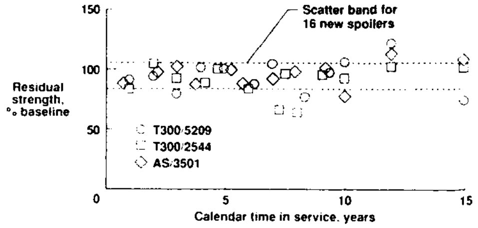

Figure 8. Residual strength of B737 graphite/epoxy spoilers.

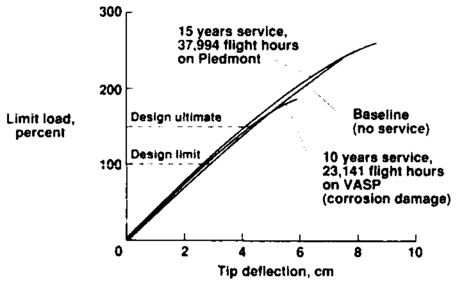

Figure 9. Load-deflection response of AS/3501 graphite/epoxy spoilers for B737 aircraft.

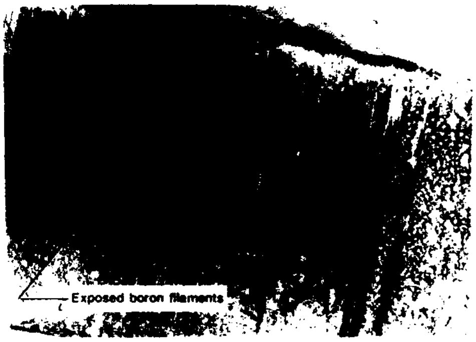

Figure 10. Corrosion damage to DC-10 boron/aluminum aft pylon skin panel.

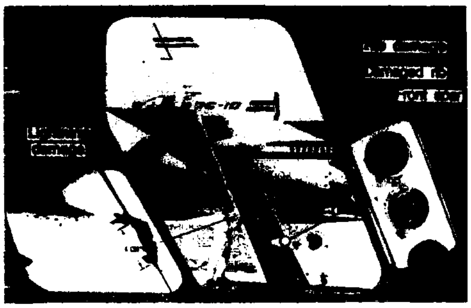

Figure 11. DC-10 graphite/epoxy rudder damage.

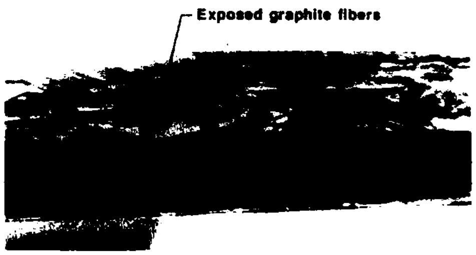

Figure 12. Lightning strike damage to DC-10 graphite/epoxy rudder trailing edge.

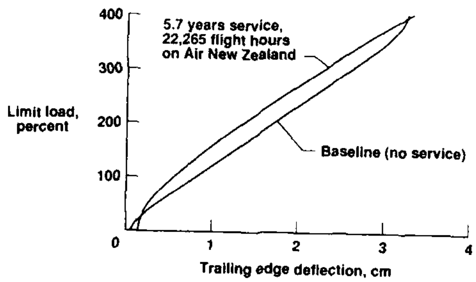

Figure 13. Load-deflection response of T300/5208 graphite/epoxy rudders for DC-10 aircraft.

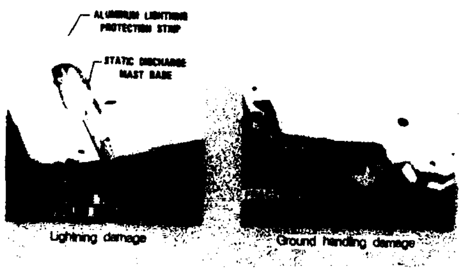

Figure 14. B727 graphite/epoxy elevator damage.

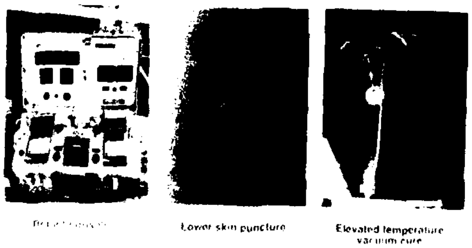

Figure 15. In-service repair of B737 graphite/epoxy horizontal stabilizer.

Figure 16. B737 graphite/epoxy horizontal stabilizer recovered from Markair crash.

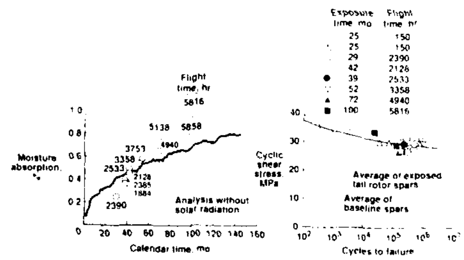

Figure 17. Moisture absorption and strength retention of AS1/6350 Sikorsky S-76 tail rotor spars.

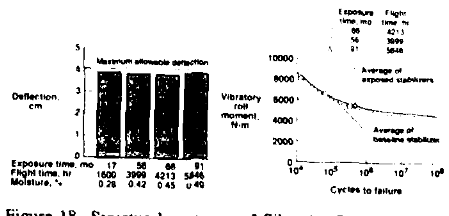

Figure 18. Structural response of Sikorsky S-76 composite horizontal stabilizers.

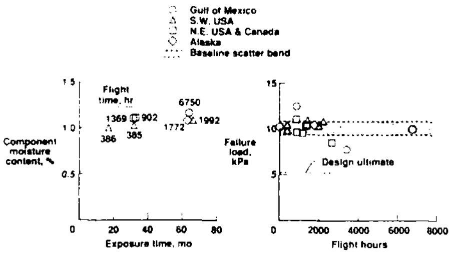

Figure 19. Moisture absorption and strength retention of T300/E-788 Bell 206L vertical fins.

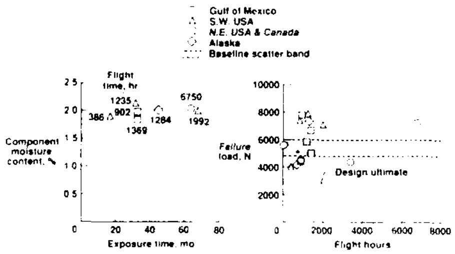

Figure 20. Moisture absorption and strength retention of Kevlar-49/F-185 Bell 206L litter doors.

- 10 yr Worldwide Ground Exposure -		- 10 yr Ground and Flight Exposure -	
Exposure Locations	**Materials**	**Exposure Locations**	**Materials**
· Hampton, VA	· T300 5209	· Edwards AFB, CA	· T300 5209
· San Diego, CA	· T300 2544	· Dallas, TX	· T300 5208
· Honolulu, HI	· T300 5208	· Honolulu, HI	· T300 934
· Frankfurt, F.R.G.	· AS/3501	· Wellington, NZ	
· Wellington, NZ	· Kevlar F155	· B737 interior	
· São Paulo, Brazil	· Kevlar F161	· B737 exterior	
Test Coupons		**Test Coupons**	
· Compression		· Compression	
· Short beam shear		· Short beam shear	
· Flexure		· Flexure	
		· Tension	
- 10 yr Bell 206L Ground Exposure -		**- 9 yr S-76 Ground Exposure -**	
Exposure Locations	**Materials**	**Exposure Locations**	**Materials**
· Hampton, VA	· T300 E-788	· Stratford, CT	· AS1 6350
· Cameron, LA	· Kevlar CE-306	· West Palm Beach, FL	· Kevlar 5143
· U.S. Gulf oil platform	· Kevlar LRF-277	**Test Coupons**	
· Toronto, Canada	· Kevlar F-185	· Compression	
· Fort Greely, AK		· Short beam shear	
Test Coupons		· Flexure	
· Compression		· Tension	
· Short beam shear			
· Tension			

Figure 21. Environmental exposure of composite coupons.

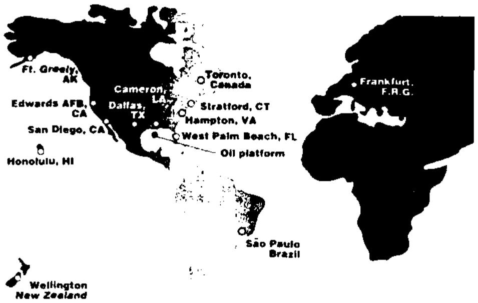

Figure 22. Geographic location of ground-based exposure racks.

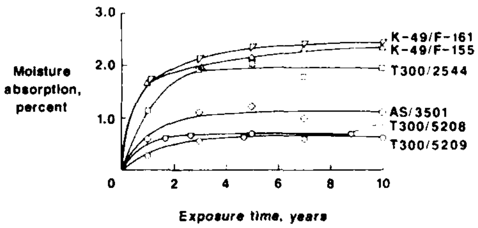

Figure 23. Moisture absorption of unpainted composite materials after worldwide outdoor exposure.

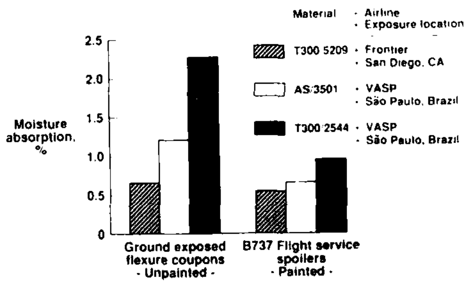

Figure 24. Moisture absorption comparison of graphite/epoxy materials after 10 years of ground and flight exposure.

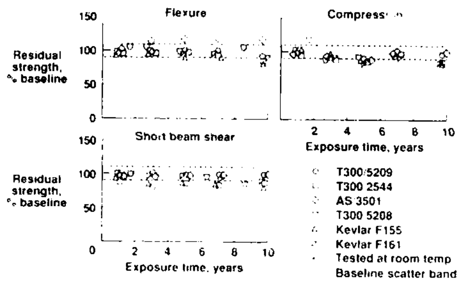

Figure 25. Residual strength of unpainted composite materials after worldwide outdoor exposure.

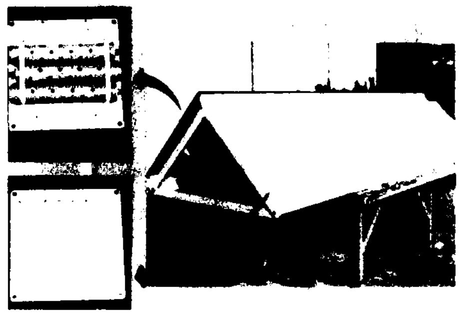

Figure 28. Boeing outdoor environmental exposure rack.

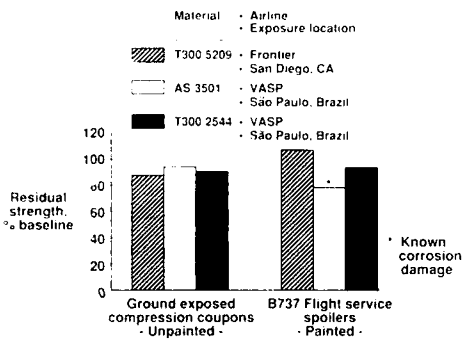

Figure 26. Strength comparison of graphite/epoxy materials after 10 years of ground and flight exposure.

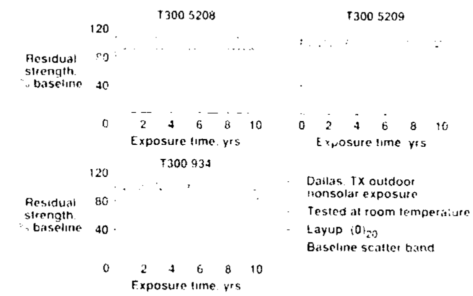

Figure 29. Effect of ground-based exposure on compression strength of painted graphite/epoxy materials.

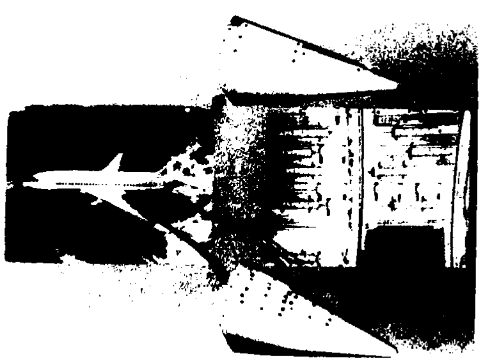

Figure 27. Boeing 737 flight environmental exposure.

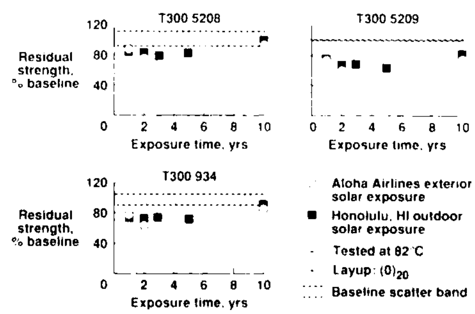

Figure 30. Effect of flight and ground-based exposure on short beam shear strength of painted graphite/epoxy materials.

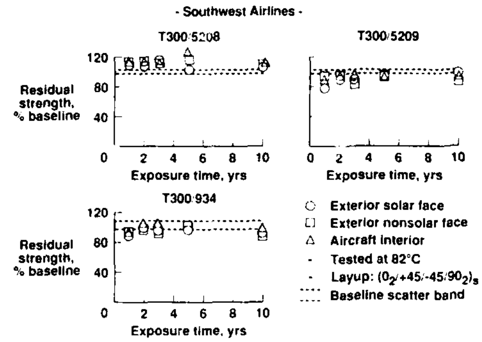

Figure 31. Effect of interior and exterior aircraft exposure on flexure strength of painted graphite/epoxy materials.

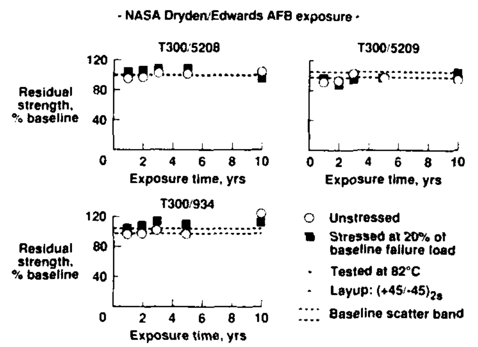

Figure 32. Effect of sustained stress on tensile strength of painted graphite/epoxy materials after outdoor exposure.

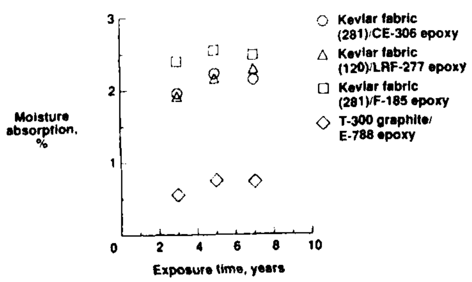

Figure 33. Moisture absorption of Bell 206L painted composite materials after outdoor exposure.

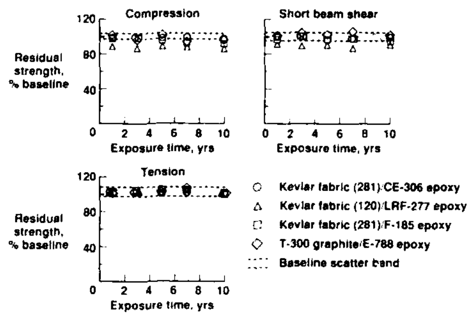

Figure 34. Residual strength of Bell 206L painted composite materials after outdoor exposure.

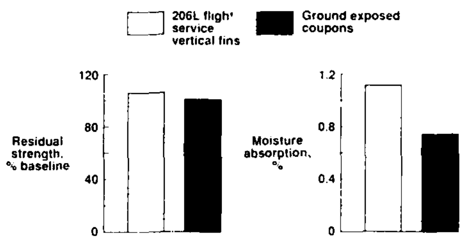

Figure 35. Strength retention and moisture absorption of T300/E-788 after 5 years of ground and flight exposure.

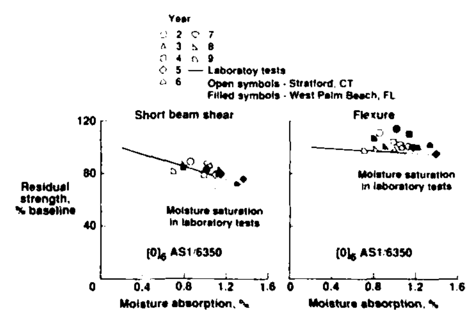

Figure 36. Effect of moisture on the residual strength of Sikorsky S-76 graphite/epoxy laminates.